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PASSIVE CONTROL OF A TOWED SONAR SYSTEM WITH HYDRODYNAMIC LIFTING SURFACES

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ABSTRACT

This paper describes the experimental methodology used to determine and optimize the performance of lifting surface devices which operate in an ill-defined turbulent flow field. The purpose of these devices is to control the aperture of a multiple line towed array sonar system. In addition to the hydrodynamic performance of the lifting surfaces, the deployment and retrieval of the towed array configuration poses a significant technical problem, which is discussed.

NOMENCLATURE

a	cylinder radius (m)
c	chord length (m)
$Re_D = U_o D/\nu$	Reynolds number based on diameter
$Re_c = U_o c/\nu$	Reynolds number based on chord length
U_o	Free stream velocity, (m/s)
x, y, z	Streamwise, transverse, depth spatial coordinates, (m)
δ	Boundary layer thickness, (m)
ν	Kinematic viscosity, (m^2/s)
ρ	Fluid density (kg/m^3)

INTRODUCTION

The use of multiple lines in a towed array system enables three-dimensional, rather than one-dimensional, measurement of underwater acoustic waves. Signal processing dictates that the absolute spatial location of each of the acoustic sensors (hydrophones) is known. Practical implementation of such a system involves towing the array lines in a specified configuration which is stable over a range of tow speeds and conditions. This technology is also applicable to other towed marine systems such as tethered submersibles or fishing rigs. The use of a single passive lifting surface device on each line, mounted upstream of the acoustic sensors, is shown to be sufficient to generate fixed lateral spreads of interest. Since, however, the device operates in a highly turbulent and ill-defined flow field, traditional airfoil theories are of limited use in predicting their hydrodynamic characteristics. Also, the existence of a wide range of turbulent eddy scales, from the order of hundredths of a millimeter to one meter, is not amenable to numerical simulations. Since a single characteristic length scale does not exist, the problem does not translate readily to tests in air either. Consequently, full-scale testing in tow tanks and water channels is necessary to design and assess the performance of the lifting surface devices and the towed array system. The large amount of development work required to implement such a system necessitates performing these types of facility tests prior to conducting sea trials of the complete, full-scale system.

The rapid prototyping technique stereolithography is used to manufacture the lifting surface devices to facilitate design optimization. This completely automated technique constructs a prototype part as a series of layers from a photo-curable, epoxy-based, liquid resin. An Argon ion laser is focused on a vat of this resin at locations defined by a CAD model of the part. As the laser strikes the liquid, the resin is cured, forming a hard solid plastic. This process continues in 0.006 inch layers until the complete part is produced. The result is a highly accurate, strong part suitable for prototype testing.

This paper describes the experimental methodology used to determine and optimize the design of the lifting surface devices. In addition, the problem of inherent cable strum is investigated. Test programs are developed for a free surface water channel and both fresh water and seawater tow tanks. Due to experimental constraints, a single line with a cone drogue (to simulate the drag of a full-length array) is utilized in the water channel to measure the amplitude and frequency of cable strum. Also, preliminary testing of the roll stability and lift force produced by the lifting surface device is performed in the water channel. In order to assure compatibility with the platform stowage tube, an inert model of the system is deployed and retrieved from a quarter-scale model of the tube placed in a fresh water tank. Finally, the seawater tow tank tests consist of full-scale tests over a range of towing speeds involving acoustically-inactive modules to ascertain system hydrodynamic performance and the lateral spread generated by the lifting surface devices.

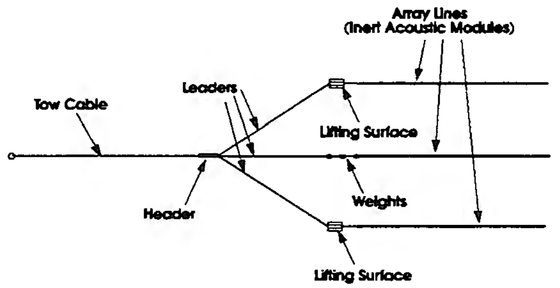
TECHNICAL ISSUES

Implementation of a multi-line towed sonar system involves a number of complex technical problems, which are best addressed in a series of experimental studies in tow tanks and water channels. The technical issues, as well as the tests designed to study them, are listed below.

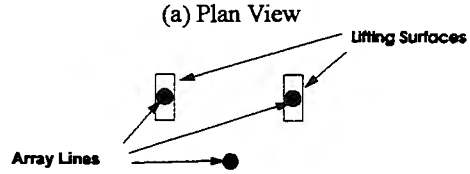
Cable Strum. A flexible cable experiencing freestream flow at a small angle to its axis will exhibit strum in the transverse direction, increasing array self-noise. The amplitude and frequency of the strum depends on the tow angle, tow speed, cable tension, cross-sectional shape, and material properties. Of these, the cross-sectional shape of the cable is the only variable design parameter. A study is performed in an open surface water channel to determine the effect of non-circular cross-section, i.e., fairing, on reducing the inherent cable strum over a range of flow conditions.

The facility used for these tests is an open surface recirculating water channel located in the Mechanical Engineering Department at the U.S. Coast Guard Academy, New London, CT. This facility runs at moderate Reynolds numbers and is designed for studies of ship hydrodynamics. The advantage of using this channel for the cable strum study is the excellent optical accessibility from all sides. Also, having the cable fixed in a moving freestream facilitates measurement of strum amplitude.

Stowage tube compatibility. One of the primary system design constraints is the requirement that the entire system be stored in and deployed (or flushed) from a fixed dimension stowage tube. This tube contains a number of three-dimensional bends, which further restrict the physical size of the lifting surface devices. In order to visualize the overall behavior of the configuration as it passes through the stowage tube, an experiment involving a transparent, quarter-scale model of the tube was designed. All dimensions, including length, diameter and bend radii were scaled from drawings of an existing, full-scale system. Also, an inert, quarter-scale model of a three-line towed sonar array was built to be flushed from the tube and then retracted using a small, hand-powered winch. The array consists of a tow cable, a header module, leader lines which hold the lifting surface devices, and the simulated acoustic modules. A schematic of the three-line array model, which accurately represents the geometry of the full size system, is shown in figure 1. When fully deployed, the two outer lines are in the same horizontal plane, with the center line located at a greater depth to create a three-dimensional aperture.



(a) Plan View



(b) End View

Figure 1 : Schematic of Three-line Towed Array Configuration

The primary focus of this qualitative study was the relative twisting of the lines and the orientation of the lifting devices as they pass through the tube bends.

This series of tests was performed in the large test tank operated by the Launchers Department of the Naval Undersea Warfare Center, Division Newport. This tank was chosen because it was long enough to house the entire quarter-scale stowage tube length as well as the array when fully-deployed. A test involving a full size system would have been impractical and too costly, and it was believed that the relevant qualitative dynamics could be determined from a scaled model of the system. The flow in the actual tube system contains a large number of turbulent scales, with the largest scale structures being on the order of the tube diameter. These large scale structures are the primary source of excitation and therefore are of most interest in this study. The appropriate velocity scale is the bulk velocity in the tube and is a parameter that can be controlled with a variable speed pump. The details of the turbulent

boundary layer, which is severely perturbed by the motion of the various components through the tube, are not considered.

Lifting device performance. As stated in the introduction, the flow past the lifting surface device used in this system is turbulent and extremely complex. For practical implementation, the towed sonar system, and therefore the lifting devices, must be stable over a range of tow speeds and conditions. Also, the lifting surface must produce side forces adequate to generate the desired lateral spread (aperture) of the array lines during operating conditions. The primary parameters of interest, therefore, are roll stability and lift force.

As a first step, a qualitative study was performed in an open surface water channel in the Mechanical Engineering Department at the U.S. Coast Guard Academy. The lifting surface device was sting mounted on low friction bearings and tested for roll stability. A load cell is used to measure the lift force produced. The current design is the result of eight years of development (a description of which is beyond the scope of this paper) and includes a weighted lower half to generate static righting moment. While this design has been shown to generate side forces adequate to produce the desired aperture during previous towing tests, the details of the flow are unknown.

In addition, the use of a technique such as particle image velocimetry would enable complete, quantitative measurements in two-dimensional flow fields to be made, providing data to optimize the design. Such a set of experiments is planned for the future.

Full system performance. The fundamental purpose of the lifting surface devices is to generate a stable lateral aperture. Vertical aperture is produced by weighting the center line. In addition, the entire configuration must be compatible with the bellmouth at the aft end of the stowage tube during inhaul and deployment.

In order to determine the hydrodynamic performance of the full three-line configuration over the range of speeds of interest, tests are planned at the high-speed seawater tow tank at NASA Langley Research Center (Brown, 1985). This facility is desirable because it is large enough to accommodate a full-size array and is capable of achieving speeds up to 68 ft/sec. The focus of this study is the hydrodynamic performance of the system, therefore, an inert array can be used.

Testing a full scale configuration ensures that the skin friction drag is represented accurately and eliminates the need for cone drogues at the aft end of the array lines. Note that the details of the spatial growth of the turbulent boundary layer (TBL) on long cylindrical arrays have not been well established. In general, Lueptow (1988) concluded that for cases where the boundary layer thickness is much less than the cylinder (array) radius, i.e. $\delta/a \leq 1$, the skin friction coefficient may be predicted using flat plate theory. For large values of δ/a, the skin friction coefficient is greater than values for a flat plate at comparable Reynolds Numbers. While this fact has been established from single point measurements, little is known about the growth of the TBL on cylinders. Furthermore, for the configuration considered here, the leader lines are at an inclination to the freestream, creating an extremely complex turbulent flow field upstream of the array lines. This, coupled with the wake of the lifting surface, make it difficult to model the flow past the array. Therefore, testing a full size configuration is the most reliable way to determine the system performance.

The full size three-line system will be towed from the carriage over a range of speeds to determine the variation in aperture. Response to various perturbations will be tested. A load cell located at the tow point will measure the total drag. Also, the configuration will be tested for compatibility with a reproduction of the full size bellmouth at low speeds.

CABLE STRUM

Tests are performed on flexible cables experiencing freestream flow at an incline to their axes in an open surface water channel. The main goals of this investigation are to determine the drag forces and strum characteristics of the cable and to study the effectiveness of a non-circular, or faired, cross-section in reducing strum.

Test Facility. The tests were conducted in the open surface recirculating water channel operated by the Mechanical Engineering Department at the U. S. Coast Guard Academy in New London, CT. A schematic of the water channel is shown in figure 2.

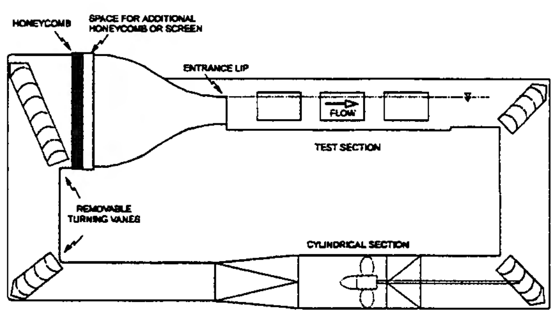


Figure 2 : Schematic of USCGA Recirculating Free Surface Water Channel

Cables of two different cross-sectional shapes were compared in these experiments. The first has a 0.5" diameter circular cross section. The second is a faired cable constructed from a 0.5" circular cable with a cast metallic fairing attached to the leading edge. The trailing edge was modified by marrying 0.25" plastic tubing to the trailing edge and wrapping all three components in tape. These cables represent sections of a leader line used to create the volumetric aperture

of the three-line array system. Since these leaders spread from a common tow point, they will experience the freestream flow at an angle to their axes.

The cables were fixed at a tow point at the upstream end of the water channel. (See figure 3, which depicts the setup prior to initiating flow.)

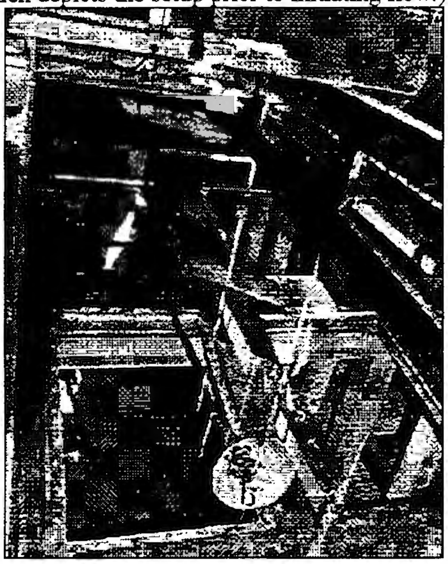


Figure 3 : Setup for Cable Strum Experiments, USCGA Water Channel

A load cell is connected to the tow point to measure the total drag on the cable. Galvanized funnels were attached to the aft end of the cables to simulate the drag that is generated by a typical array. The drag produced is a function of the form of the funnel and the speed of the water. These funnel drogues cause the cables to hang at angles of attack between 0° and 8°. The angle at a given speed can be varied by adjusting the amount of weight inside the funnel. The cable was observed in flow speeds up to 7 ft/sec and the strum characteristics recorded via an underwater camera.

Results. When the funnels and the circular cable were in the flow, only a small portion of the overall drag force resulted from the cable itself. The drag force, on average, was less than 1 lb for all angles of attack. This circular cross-section cable displayed very noticeable strum at all speeds, with strum magnitude on the order of the cable radius and generally increasing up to a freestream speed of 5 ft/sec. At higher speeds, the strum frequency increased and the magnitude decreased. Preliminary estimates for strum frequency are on the order of 100 Hz.

The weight of the faired cable (metallic leading edge) made it difficult to attain the desired angles of attack and maintain the proper orientation to the flow. A multiple funnel system was developed to generate sufficient drag to lift the cable off of the channel floor. With this system, the faired cable exhibited a marked reduction in strum magnitude. However, the cable displayed a tendency to roll 90° rather than fly in the most effective drag orientation. This is likely a result of asymmetry in the cable which causes a lateral torque.

These experiments demonstrated that adding fairing to a flexible cable can reduce the strum significantly. However, it is evident that the fairing design must take into account the desired weighting of the cable and must be symmetric so that it remains in the proper orientation. These issues may preclude practical implementation of a faired leader cable.

STOWAGE TUBE COMPATIBILITY

A series of experiments were conducted in a quarter-scale test facility to allow observation of the behavior of the three-line array configuration as it passed through the full three-dimensional bends of fixed dimension stowage tube. The goal was to identify potential risks to proper deployment of the system to the desired configuration. This included the effects of flushing flow rate, flow conditions in the tube and interaction with the tube bellmouth. Particular attention was given to the behavior of the lifting surface devices in the tube bend section and their performance under various simulated freestream conditions.

Test Facility. The tests were performed in the large test tank operated by the Launchers Department, Code 83, and located in building 1246, NUWC Division Newport. A schematic plan view of the setup is shown in figure 4.

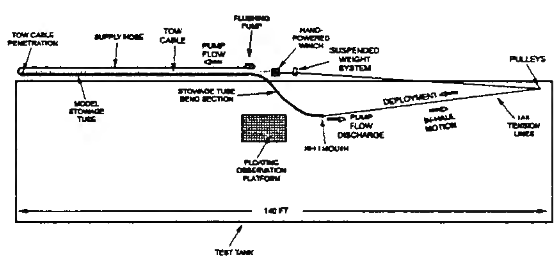


Figure 4 : Schematic of Quarter-Scale Stowage Tube Test Setup (Plan View)

The quarter-scale model of the stowage tube consisted of a straight hose section mounted along the tank railing and a bend section that turns through three bends leading into the tank and terminating at a bellmouth submerged just below the surface. Since the bend section was constructed of transparent acrylic, it was possible to view the behavior of the header/leader/array configuration as it passed through tube. Note, however, that this material change prevents an accurate reproduction of the friction forces in the actual system.

The inert, quarter-scale model of the three-line array simulated all the components of the actual array as shown in figure 1. The following table lists each component with the material used to model it at quarter-scale.

Component	Model Material
Tow Cable	Kevlar Line
Header Module	Water-Filled Polyurethane Hose
Leader Lines	Coax Cable
Acoustic Modules	Rope

The three leader lines and the corresponding acoustic modules were three different colors to allow relative twisting of the lines to be monitored. Completing the three-line array model were quarter-scale lifting surfaces manufactured via stereolithography.

The array was flushed from the stowage tube via flow provided by a one horsepower, centrifugal pump. This pump could deliver flow velocities and discharge pressures comparable to that provided by the actual flushing system. To pull the array into the stowage tube, the tow cable was wrapped onto a hand-powered winch, simulating the towed array handling system. Hydrodynamic drag that would be produced by the freestream flow during deployment and inhaul of the actual system was simulated by weighted tail tension lines. These thin kevlar lines were attached to the aft end of each of the array lines, passed through a pulley system with suspended weights and then wrapped onto the winch in the opposite direction of the tow cable. As the array was cycled through successive inhauls and deployments, the behavior of the system was recorded with a hand-held, underwater camera.

Results. Observation of the basic configuration during inhaul and deployment revealed several characteristic features of the dynamics of the passage through the tube. The header module, leader lines and the lifting surfaces generate twist in the leader system as it passes through the bends. This twist is cumulative upon successive cycles of inhaul and deployment and is not always integrated, i.e., one or two lines may twist around the others, as illustrated in figure 5. The center leader line appeared to drop between the other two leaders while the configuration was inverted in the tube. The lifting surface devices also rotated in the tube, often independently, so that their relative orientation changed. Consequently, upon deployment, at least one would exit the bellmouth in an inverted position. (It is anticipated that a freestream flow would aid in correcting the orientation of the lifting surfaces, however, this could not be shown conclusively from this test. Full-scale tests at appropriate speeds are required.) These observations indicate that an unconstrained leader system will generate a large amount of twist, which will affect the deployment of the array configuration to the proper aperture.

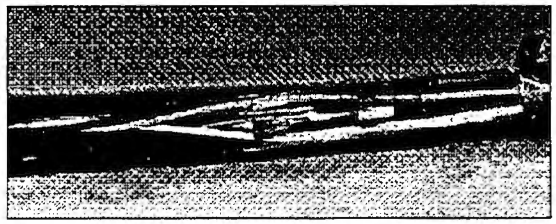


Figure 5 : Leader System in Stowage Tube Showing Twisting of Individual Lines

The lifting surface devices were tested individually in a simulated freestream to demonstrate their performance under various flow conditions. As the lifting surfaces were subjected to perturbations such as high levels of turbulence from a jet and deflection of the incoming flow field, they maintained their proper orientation, never rolling more than 90°. While these observations indicate that the devices are relatively stable, it is not conclusive, since hydrostatic righting moment, lift and bearing friction were not scaled equally. Further tests are necessary to determine their stability under full-scale conditions.

Finally, dye injection was used to visualize the flow in the tube bend sections and determine the degree of swirl. In addition, a very thin kevlar line was inserted into the tube bend section to determine the dominant flow path. In general, no significant, large scale swirl was observed in the tube via dye visualization. The mean freestream flow dominates at this Reynolds Number (Re_D, based on tube diameter, is on the order of 10^6). When the thin kevlar line was inserted in the tube, it entered the bend section at the centerline. As it passed through the bends, it took the shortest path through the bends, i.e., it hugged the wall at the inside of each bend, and returned to the centerline as it exited the bellmouth. Since this behavior was observed even at low flow velocities and no tension was applied to the line, it can be concluded that the turbulence induced vibrations are not sufficient to generate large scale twisting and that the freestream flow is dominant.

These tests provided valuable insight into the behavior of the three-line array configuration as it undergoes successive cycles of inhaul and deployment from a stowage tube. Although a relatively simple, low cost setup was used, it yielded results that could not be obtained at any other existing facility. The understanding of the behavior of the multi-line system as it moves through the stowage tube has been improved. It can be concluded that the rotation of the array configuration in the tube is driven primarily by the rotation of the header, leaders, and lifting surface devices in the tube bends. The twist generated as the lines pass through the stowage tube bends accumulates during successive cycles of inhaul and deployment and could have a significant effect on the ability of the configuration to achieve the desired aperture. Since no significant swirl was observed in the tube, any flushing flow effects that might induce twist are an order of

magnitude less than the dynamics of the passage of the system through the tube bends.

LIFTING DEVICE PERFORMANCE

Tests of the performance of the lifting surface device were conducted in a recirculating water channel at the U. S. Coast Guard Academy (USCGA) in New London, CT. The primary objectives were to obtain preliminary measurements of the lift force produced and to evaluate the righting moment created by ballasting (weighting) the lower half of the device.

Test Facility. The tests were conducted in the open surface recirculating water channel operated by the Mechanical Engineering Department at the USCGA. The lifting surface, shown in figure 6, was mounted on a sting aligned with the freestream, i.e. approximately zero angle of attack. The yaw angle could be adjusted to ±10°. Side force was measured via a load cell as shown in figure 7. Uncertainties are introduced in these measurements due to the resistance of the sting apparatus to lateral motion. Effects of the tether in the crossflow were minimized by using a 0.020" diameter stainless steel wire which was pretensioned to eliminate any visible strum or catenary. The side force measurements obtained were compared to previous lift measurements in another facility with reasonable agreement.

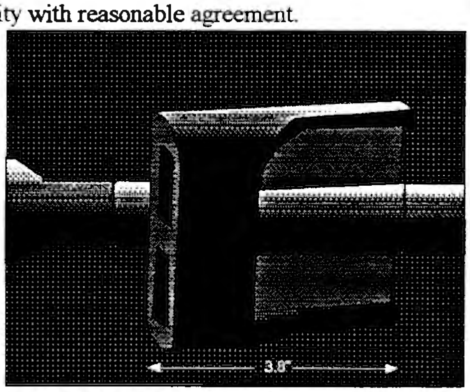


Figure 6 : Lifting Surface Device

Tests were conducted at speeds up to 7.5 ft/sec ($Re_c \approx 2 \times 10^5$). First, the stability of the lifting surface in roll was investigated at 0° and 10° nose up (yaw) and recorded with an underwater video camera mounted on the sting. The lifting surface then was constrained from rolling and the lift force was measured over the range of flow speeds at 0° yaw angle. Finally, dye injection was used to qualitatively investigate the degree of separation and the mean streamlines around the lifting surface at low speeds.

Results. Tests of the lifting surface device in a free-to-roll condition demonstrated that it will roll to moderate angles even at 0° yaw angle. The roll angle increased with speed, with values up to approximately 10° at the highest speeds tested. In general, the amount of oscillation in roll decreased relative to that observed during testing of previous designs. This is due most likely to increased surface symmetry produced by the highly accurate stereolithography

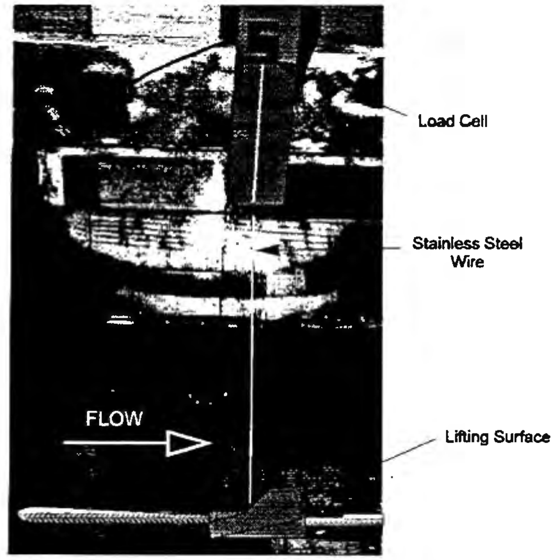


Figure 7 : Side Force Measurement Via Load Cell Apparatus

manufacturing process. When the wing was oriented at 10° nose up, values up to approximately 40° were observed. While these roll angles are within an acceptable range, the speed dependence suggests that system stability could be threatened at higher speeds. Consequently, the next generation of lifting surfaces will have additional ballast in the lower half of the wing as well as buoyant material in the upper half of the wing to increase the static righting moment.

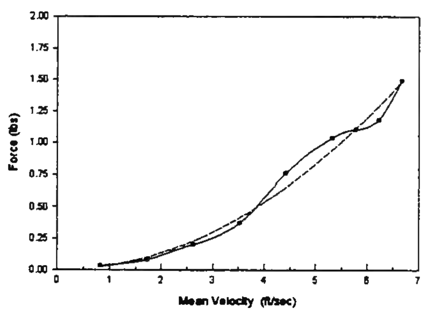


Figure 8 : Side Force versus Mean Velocity

The values of measured force are plotted versus pump speed as the solid line in figure 8. A curve fit (dashed line) verifies that the force varies with the speed squared. Although the system used to obtain these measurements contains some inherent uncertainties, the force values agree with previous measurements within 15%. It is concluded that the current design of the lifting surface generates sufficient

lateral force to produce the desired configuration aperture.

Qualitative visualization of the flow field around the lifting surface at 2.0 and 4.0 ft/sec was obtained via dye injection. Even at these low velocities, the flow was observed to separate very close to the leading edge of the low pressure side of the lifting surface. Dye patterns over the high pressure side suggest that the flow is unseparated and turbulent over most of the surface. Figure 9 shows a view of the flow past the lifting surface from the low pressure side. The streaklines represent the composite of dye injection at discrete points on the high pressure side of the lifting surface. Note that a pronounced vortex wraps from the high pressure side over the wing tip to the low pressure side, as evidenced by the streaklines. Although this may lead to flow reattachment on the low pressure side, it does not contribute any significant lift, since the flow originates on the high pressure side.

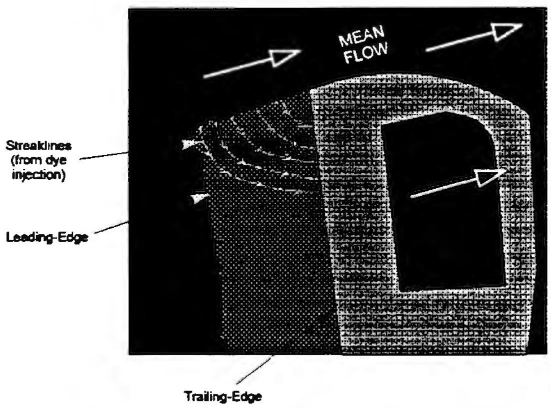


Figure 9 : Flow Visualization around the Lifting Surface

In general, these tests provided sufficient data to proceed with the fabrication of the next generation of the lifting surface device. The primary design changes include modifications to increase the static righting moment of the wing. Measurements of side force indicate that this lifting surface produces adequate lift to generate the desired array aperture. Also, observations of the lifting surface when it is free on its bearings show that it is relatively stable in roll. Finally, dye visualization demonstrates that the flow field around the lifting surface is highly turbulent and extremely complex.

FULL SYSTEM PERFORMANCE

As stated in the Introduction, the complexity of this system and the Reynolds numbers of interest make numerical or theoretical studies insufficient to measure its hydrodynamic performance. Therefore, tests of the full-scale, electrically inert three-line system are planned to determine the hydrodynamic performance of the configuration over the complete range of speeds of interest. Of primary concern is the vertical and horizontal aperture generated and the overall stability of the configuration.

Test Facility. Tests will be performed at the high speed seawater tow tank at the NASA Langley Research Center in Hampton, VA. A full size, acoustically inert three-line array will be towed from a submerged tow fixture at speeds up to 68 ft/sec, as shown schematically in figure 10. Total system drag will be measured by an underwater load cell mounted in line with the tow fixture. The behavior of the array will be recorded via underwater video cameras. One camera will be mounted approximately twelve feet behind the tow carriage, focusing on the behavior of the lifting surfaces (see figure 10). A second camera will be used to capture the behavior of the array during steady tow and during deployment and retrieval from a full-scale bellmouth.

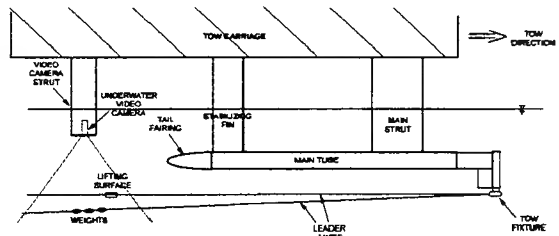


Figure 10 : Configuration for Baseline Full-Scale Tests

The inert, full-scale model of the three-line system contains all the physical components of the actual array except for the tow cable. To tow the system, the header module will be attached to the tow fixture via a fitting designed specifically for this test. Lifting surface devices manufactured via stereolithography with the modifications described in the previous section will be included in the inert array configuration.

Test Plan. The baseline full-scale array configuration will be attached to the tow fixture as shown in figure 10 and towed over a range of speeds. These initial runs will be used to define the aperture variation with speed and to verify the adequacy of the lifting surface device in terms of force production and roll stability. An important aspect to the generation of the desired aperture is the weighting of the center leader line, which will be adjusted during these tests as necessary. Modeling indicates that this line will be at angles of attack greater than 5° at low speeds, so that strum will be an issue as well. To complete this series of tests, array survival at 68 ft/sec will be assessed.

The configuration then will be tested in a variety of adverse flow conditions. First, the ability of the full configuration to recover from perturbations will be evaluated. These perturbations will be produced by upstream vortex generators and manual manipulation of the array lines. The behavior of the individual lifting surfaces when subjected to a vortical flow field

will be assessed also. Next, the compatibility of the configuration with the bellmouth will be examined. A reproduction of the full scale bellmouth that is located at the end of the actual stowage tube will be mounted below the main tube as shown in figure 11. As the three-line array is retrieved and deployed from the bellmouth at low speeds, potential risks to proper operation will be identified and recorded via carriage-mounted underwater video cameras. Also, the ability of the freestream flow to correct the orientation of the leader lines and the lifting surfaces after they exit the bellmouth (as observed in the quarter-scale tests) will be evaluated.

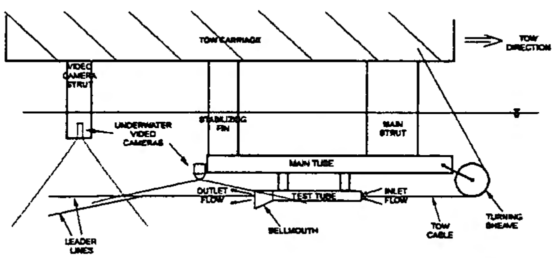


Figure 11 : Configuration for Full-Scale Tests of Bellmouth Compatibility

Finally, variations to the baseline configuration will be tested. Based on the strum characteristics observed in tests of the full-scale, baseline configuration and in the USCGA water channel tests, the form of the center leader line will be varied. This series of tests will determine the effectiveness of fairing a circular cable and define the form of the center leader line. In the final series of runs, a preliminary assessment of a system for retracting the leader lines will be performed. It is hypothesized that holding the lines together will maintain their relative orientation and decrease the amount of twisting that occurs in the stowage tube bend section.

These tests are designed to measure the hydrodynamic performance of the full three-line array configuration. System stability and aperture generation will be ascertained over the range of speeds of interest. The results of these tests will determine the form and weight of the center leader, identify necessary modifications to the lifting surfaces, and reveal potential obstacles to long term system operation.

CONCLUSIONS

The performance of lifting surface devices as a means to generate a volumetric aperture in a towed sonar system was investigated. A series of experiments were conducted in a free surface water channel and in fresh and sea water tow tanks. The complexity of the flow makes the problem tractable only experimentally. Although relatively low cost and primarily qualitative, this test program was successful in addressing a number of technical issues involved in the practical implementation of a multi-line towed array system.

In particular, it was determined that the current lifting surface design produces sufficient lift to generate the desired lateral spread of the array lines. Important insight into the behavior of the lifting surface lead to minor design modifications. Tests of a quarter-scale system revealed valuable information about the system dynamics during deployment and retrieval from a stowage tube. Inherent strum of a cable at a small angle of attack to the freestream was characterized and will be used to optimize the form of the center leader line that generates the vertical spread of the array lines. Finally, a test of the full-scale, three-line system is planned.

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